CHAPTER TWENTY-SEVEN

Climate Change, Food, and Biodiversity

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INTRODUCTION

Most human nutrition is derived from domesticated plants. Significant factors controlling the productivity of agricultural crops are under human control; fundamentally their evolution is in our hands. As Sir Otto Frankel once remarked, we have acquired "evolutionary responsibility" for them. A discussion about the impact of climate change on agriculture cannot, therefore, be about climate's effects on only plants and agricultural ecosystems. It must also concern how we discharge our evolutionary responsibility and assist agriculture in adapting to dramatically new conditions.

Agriculture—plant and animal domestication—arose in multiple locations around the world in the early and middle Holocene and thereafter spread globally (Larson et al. 2014). As a consequence of the transition from hunting and gathering to agriculture, human beings became increasingly dependent on the vagaries of weather, as sedentary farmers' livelihoods are more sensitive to fluctuations in temperature and rainfall than those of nomadic hunter-gatherers.

Over time, exposure to different environments, climates, and human cultures helped generate and sustain enormous genetic diversity within the gene pools of the different domesticated crops. According to the statistics of the Food and Agriculture Organization of the United Nations, wheat, which originated in the Near East as a crop, is now grown in 124 countries, and maize, domesticated in the Americas, is cultivated in 166 countries (FAO 2014). Thus, the ecological niche of agricultural subsistence is wide, but climate change is about to alter the climatic parameters of that niche in an unprecedented way in many parts of

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the world. There is evidence that agricultural production is already being substantially and negatively affected by changes in climate, and projections based on climate models indicate that later in this century many farming areas will have climates not experienced during the entire history of agriculture. We are seeing an increasing mismatch between our crops and the human-altered environment (Carroll et al. 2014).

One in eight persons on Earth today, or more than 795 million in total, are already considered food insecure (FAO, IFAD, and WFP 2016). Most undernourished people live in South and East Asia and Sub-Saharan Africa. Although the challenge of adapting agriculture to new environmental circumstances will be global, posing an obstacle to development goals at all levels, it will take on a particularly urgent humanitarian aspect where the poor and food insecure are concentrated, where the impacts of climate change on food production tragically will be most severe.

IMPACTS

Crop yield is the most studied aspect of the impacts of climate change on food security. A large number of studies document that effects are already evident in several regions and project increasingly negative effects on yield. Climate extremes including unusually hot night- and daytime temperatures as well as natural disasters attributed to anthropogenic activity have already negatively affected overall crop production (Porter et al. 2014). A study at the International Rice Research Institute (IRRI) found that a 1°C increase in minimum temperature during the dry growing season had the effect of reducing rice yields by 10 percent (Peng et al. 2004). Lobell et al. (2011) found that global maize production declined 3.8 percent and wheat declined 5.5 percent between 1980 and 2008 compared to a counterfactual without climate change.

There are two principal types of studies estimating effects of climate change on future crop yield: statistical models relying on historical yield and weather data, and biophysical or process-based models relying on data from experimental crop trials (Porter et al. 2014; Lobell and Burke 2010). A recent global meta-level study that synthesized projections from more than 1,700 published simulations to evaluate yield impacts of climate change concluded: "There is a majority consensus that yield changes will be negative from the 2030s onwards. More than 70 percent of the projections indicate yield decreases for the 2040s and 2050s, and more than 45 percent of all projections for the second half of the century indicate yield decreases greater than 10 percent" (Challinor et al. 2014, 289). The picture emerging from these models is dire. At a global aggregate level, yields of maize and wheat begin to decline with 1°C–2°C of warming in the tropics, while temperate maize and tropical rice yields are significantly affected with warming of 3°C–5°C (Porter et al. 2014).

These global estimates mask considerable regional differences, however. Studies projecting positive effects on crop production in temperate regions buffer some of the anticipated decreases in yields in tropical regions for which there is strong consensus (Challinor et al. 2014). But the latest report from the International Panel of Climate Change (IPCC) (Porter et al. 2014) says it is now less likely that moderate warming will raise crop yields at mid- to high latitudes than projected in their previous assessment. Instead, the IPPC projects that there will be more yield decreases than increases even under moderate warming.

Sub-Saharan Africa is emerging as a region that will be particularly hard hit by climate change. On the basis of national historical climate and crop production data, Schlenker and Lobell (2010) projected aggregate production losses of 17 percent for sorghum and 22 percent for maize in the region by midcentury (Schlenker and Lobell 2010). Lobell et al. (2011) analyzed experimental yield data from 20,000 maize trials across South and East Africa and projected that 1°C warming will lead to yield losses in 65 percent–100 percent of the regions' maize growing areas. They found significant varietal differences depending on the maturity period of the varieties and on whether the variety is hybrid or open pollinated (Lobell et al. 2011). At a local level in this region, Thornton et al. (2009) used a biophysical crop model to estimate effects in grids corresponding to ~18 km by 18 km in the landscape and found that between 9 percent and 33 percent of the assessed grids across East Africa are likely to see a potential yield loss of more than 20 percent for maize by 2050.

Impact studies generally agree that the effect of temperature increase will be more important than changes in precipitation and that the benefits of increased CO_2 in the atmosphere for photosynthesis will be outweighed by the negative effects of temperature increase (Lobell and Gourdji 2012; Thornton et al. 2009). Excessive heat can harm virtually all plant parts and affect plant growth at every stage in the life cycle. The life cycle and growth period are shortened. Leaves curl and wither, reducing light interception. Partial closure of stomata to reduce transpiration increases canopy temperature and reduces photosynthesis effectiveness. The quantity, quality, and timing of growth in reproductive tissue are reduced (Cairns et al. 2013; Cossani and Reynolds 2012). Thus, negative effects of heat both cause and compound already existing moisture deficiencies. Most yield projections omit consideration of pest, weed, and disease impacts on crop yields, but several studies conclude that changes in climate and CO_2 concentration will alter the distribution and probably increase the competitiveness of nematodes, insects, fungal diseases, and weeds in many areas (Ziska et al. 2011; Porter et al. 2014). Effects on other biotic factors important for crop production such as on soil communities are underresearched but also represent potential threats to agricultural production.

At 2°C of global warming, many crops will begin to enter a new, historically unprecedented climate territory. New climates will generate combinations of conditions and biological assemblages with no current analogues (Burke, Lobell, and Guarino 2009). Changes in climate extremes can have more adverse impacts on crop production than changes in means. Moreover, today's extremes might become tomorrow's normal—today's hot growing seasons, which often result in large declines in food production, could become the cool and "best" growing seasons of the future (Figure 27.1). The damage done by short-run events could become long-term trends without sufficient investments in adaptation (Battisti and Naylor 2009). A recent statistical study of global crop production and extreme weather events found that droughts and extreme heat have reduced national cereal production by 9 percent–10 percent and 8 percent–11 percent more damage in developed countries than in developing ones (Lesk, Rowhani, and Ramankutty 2016). This is dire evidence in light of the estimate that by 2050, the majority of African countries will experience climates over at least half their current crop area that lie outside the range currently experienced within the country (Burke, Lobell, and Guarino 2009).

Evidence presented in previous chapters of this book suggests substantial risks to wild plant biodiversity due to range shifts and contraction in habitats with suitable climates. In a seminal study, Thomas et al. (2004) predicted that 15 percent–37 percent of wild plant biodiversity is threatened with extinction due to climate change by 2050. Similar projections have been made for crop wild relatives. Jarvis et al. (2008) estimates that up to 61 percent of wild peanut (*Arachis*) species, 12 percent of potato (*Solanum*) species, and 8 percent of cowpea (*Vigna*) species could become extinct within 50 years due to climate change. Other ecological niche modeling studies have projected large contractions in distribution areas for wild relatives in the Cucurbitacea

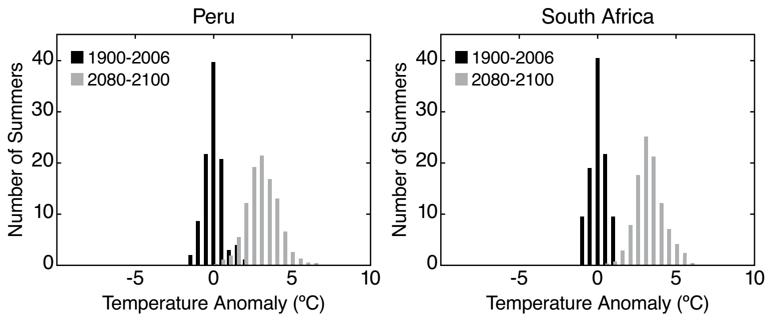


Figure 27.1. Historic and future average growing conditions in Peru and South Africa. (Data from Battisti and Naylor 2009.)

family (to which pumpkins and squashes belong) in Mexico (Lira, Téllez, and Dávila 2009), on wild relatives of maize (*Zea*) in Mexico (Ureta et al. 2012), and wild Arabica coffee (*Coffea arabica*) in Ethiopia (Davis et al. 2012). Like wild plant biodiversity, crop wild relatives will face many compounding influences such as habitat degradation due to agriculture and human infrastructure, and shifts in pests and disease stress.

CLIMATE CHANGE AND FOOD SECURITY

Future food security will be affected not only by crop production levels but also by a host of socioeconomic factors that make it difficult to link climate change unambiguously to impacts on food security (Lobell and Gourdji 2012; HLPE 2012). Nevertheless, the IPCC highlights that climate change is likely to affect all aspects of food security, not only food availability, but also food access, utilization, and price stability (Porter et al. 2014). Nutritional quality of food and fodder (important for the utilization aspect of food security) is negatively affected by elevated CO_2 (Myers et al. 2014; Porter et al. 2014). Climate extremes have, together with other factors, played a role in periods of rapid food and cereal price increases (important for access and stability aspects of food security) in recent years. Yield losses in wheat and maize caused by already evident climate change between 1980 and 2008 resulted in an estimated average commodity price increase of 6.9 percent compared to a counterfactual with no climate change in the period (Lobell, Schlenker, and Costa-Roberts 2011). Projecting this trend into the future, the IPCC finds that changes in temperature and precipitation, without considering effects of CO_2, will contribute to increased global food prices in the range of 3 percent–84 percent by 2050 (Porter et al. 2014).

Periods of abnormally hot weather in the past provide an imperfect but important glimpse of how we might expect agricultural and social systems to react in the future unless food production keeps pace with the growing demand. Significant climate events due primarily, it is argued, to their impact on food production have been positively correlated with increased incidents of war and civil strife over the past 2,000 years (Büntgen et al. 2011; Hsiang, Burke, and Miguel 2013). As for food security, the effect of climate change on human security will heavily depend on political and economic pathways taken (Theisen, Gleditsch, and Buhaug 2013), but the link between climate-caused food scarcity and social instability is arguably an underlying trend in human history. Analyzing new conflict event data covering Asia and Africa in the period 1989–2014, von Uexkull et al. (2016) found that for groups depending on agriculture living in poor countries and experiencing political exclusion, droughts significantly increased the likelihood of violence.

PREPARING FOR CLIMATE CHANGE THROUGH CROP ADAPTATION

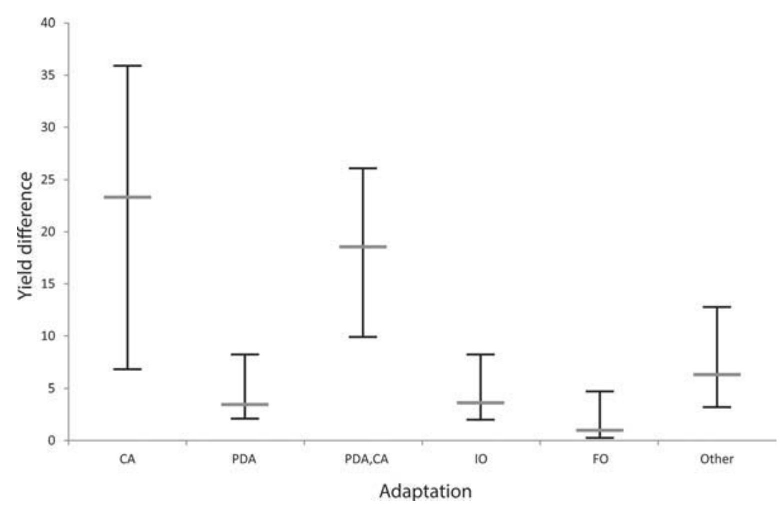
As the twenty-first century progresses, a central question becomes whether, to what extent, and through which means agriculture will successfully adapt to climate change. This question is critical to food security, to global peace, and to the environment, because agricultural systems that function poorly are a threat to all.

Challinor et al. (2014) assess several common adaptation strategies in agriculture: cultivar adjustment, planting date adjustment, and irrigation and fertilizer optimization. Cultivar adjustment is estimated to be the most effective measure with a median potential to increase yield by 23 percent compared with situations where farmers do not change cultivars (Figure 27.2).

Cultivar adjustment refers to switching to a presumably better adapted variety, be it a local or an improved variety and can involve both formal and informal seed supply systems (Westengen and Brysting 2014). Recent typologies of adaptation distinguish between incremental, systemic, and transformative adaptation options (Vermeulen et al. 2013; Porter et al. 2014; Rippke et al. 2016) In this typology, cultivar adjustment involving local varieties and informal seed supply systems exemplifies incremental adaptation as they are "based on long experience in dealing with a highly variable environment" (Vermeulen et al. 2013), while those involving improved varieties are classified either as incremental or systemic change, depending on whether the varieties are available off the shelves or are developed through targeted breeding programs. The cardinal question is whether farmers and breeders will be able to adapt based on the genetic variability in traditional and improved varieties. Early research into this question indicates that although there is great genetic potential in available genetic resources, there are challenges regarding access to the appropriate genetic resources, both for farmers and for breeders (Burke, Lobell, and Guarino 2009; Bellon, Hodson, and Hellin 2011; Bjørnstad, Tekle, and Göransson 2013).

Adaptation of crops to warmer new climates will not be reliably—and certainly not

Figure 27.2. The percentage benefit (yield difference between cases with and without the adaptation) for different crop management adaptations: cultivar adjustment (CA); planting date adjustment (PDA); adjusting planting date in combination with cultivar adjustment (PDA, CA); irrigation optimization (IO); fertilizer optimization (FO); other management adaptations (Other). The simulated median benefit is marked with a solid, dark gray, horizontal line and the whiskers indicate the 25th and 75th percentile. (Based on data from Challinor et al. 2014; Porter et al. 2014.)



always—achieved by shifting production of current varieties to cooler climates. Such shifts involve changes in photoperiod, rainfall timing, pests and diseases, and involvement of other flora and soil types, making adaptation a nontrivial event. Incremental crop adaptation to environmental change by on-farm selection of local populations has dominated the 10,000-year history of agriculture; this is still the major pathway to crop adaptation for many crops in developing countries where informal seed systems dominate. Local varieties called landraces typically have a long history in their particular, often limited human and ecological communities and are adapted to those specific niches. But given the rapidity and scale of the projected climate change, landraces may experience a loss of the adaptive advantages they currently have. We cannot assume that landraces will routinely "evolve their way" into new climate regimes. Scientific plant breeders typically have access to a larger gene pool than farmers working with landraces, and therefore have a larger toolbox of genetic traits as well as technologies to draw on when developing new varieties. Integration of formal and informal seed system institutions and collaboration between farmers and breeders will be needed to harness the strengths of local and scientific knowledge (McGuire and Sperling 2013; Challinor et al. 2016; Westengen and Brysting 2014).

Because farmers and their crops are headed into uncharted territory, the employment not just of the primary but also of the secondary and tertiary gene pools of crops will likely be useful in deploying important adaptive traits. Crop wild relatives are increasingly recognized as a key resource for adapting crop species to climate change (McCouch et al. 2013). Successful utilization of genetic resources from other countries and from crop wild relatives in plant breeding relies on functioning policies, economic and scientific factors on the supply side as well as policies and socioeconomic factors on the demand side.

The alternative to adaptation on existing farmland will often be expansion of agriculture into nearby natural habitats. A recent study modeling climate change effects on global wine-grape production shows how agricultural adaptation may affect ecosystems negatively if farmers respond to declining climate suitability in traditional wine-growing areas by expanding into wildlife habitats (Hannah et al. 2013). Such indirect effects of climate change on biodiversity exacerbate direct impacts described in previous chapters of this book.

In addition to the five agricultural adaptation strategies described above, there are also a range of other adaptation strategies used by farmers around the world, some on-farm and some off-farm strategies. The options are widely different for a large corn farmer in Iowa, in the United States, compared to those available to a small-scale farmer in Morogoro, in Tanzania. Cultivar adjustment alone is unlikely to be a sufficient response, but without it other measures cannot succeed.

INSTITUTIONAL PREPAREDNESS: GAPS AND PROGRESS

Because new crop varieties typically take a decade or for some crops much longer to develop and deploy, the impact of climate change on agriculture and food becomes, to some extent, a question of how well prepared we are to begin to produce these new adapted varieties for the expected climate of 2025 and beyond. In other words, do we have access to the needed raw material?

Collecting of economic plants dates to 4500 BP. From the sixteenth century, botanical gardens were heavily involved. The geneticist N. I. Vavilov in the former Soviet Union organized the first systematic large-scale collections of crop diversity in the 1920s, which were conserved in St. Petersburg (then Leningrad) and used for plant breeding and research (Plucknett et al. 1987). The United States established its national genebank in 1954. Today, FAO records some 1,750 genetic resource collections housing more than 7 million samples. There is currently much duplication of conservation efforts, with the same samples held by several genebanks, and the FAO estimates that only 25 percent–30 percent of the total number of samples are unique (FAO 2010). This duplication of conservation efforts and proliferation of genebanks would not be a concern were it not for the fact that only a few of them actually offer secure long-term conservation and access (FAO 2010). A partial solution—an opportunity to solve this problem—is provided by the legal framework provided by the International Treaty on Plant Genetic Resources (ITPGRFA) and the institutional support provided by the Global Crop Diversity Trust, both crucial instruments for the development of an efficient and sustainable system of *ex situ* conservation called for by the FAO (2010).

Plant-breeding expertise and investment is focused on a small number of commercial crops, with maize at the top of the list. Perhaps half of all domesticated crops have never had a single Mendelian-trained plant breeder working with them (Fowler and Hodgkin 2004). Even crops of tremendous importance (e.g., banana, yam) have fewer than 10 plant breeders (Fowler and Hodgkin 2004). This would indicate a severe lack of capacity to develop adapted new varieties quickly. Furthermore, as many as a billion people live in farm families that are largely self-provisioning in terms of seeds; these are families mainly in developing countries with limited access to the genetic resources outside their own communities that might be needed for crop adaptation to significant climate change through on-farm selection and breeding. Genetic diversity and the diffusion of diversity such as took place with the massive government seed distribution in the United States in the 1800s (Fowler 1994) have heretofore enabled wide adaption, but no large-scale programs exist today to provide this diversity to farmers who by default are the sole plant breeders for many crops.

Although plant genetic resource collections are numerically large globally, there are questions about the adequacy of collections for many individual crops (Fowler and Hodgkin 2004); moreover, no country is even remotely independent or self-reliant in terms of the resources they will need in the future for plant breeding. Every country is in some way dependent on others (Khoury et al. 2016). Figure 27.1 shows how dramatically the growing climates might change in individual countries, a reminder of countries' interdependency in terms of crop genetic resources needed to sustain breeding and production. Recognizing this interdependency, the ITPGRFA mandates "facilitated access" among its member states, but a recent survey shows that fewer than 40 percent are providing access; many genebanks do not respond to requests or deny them outright. Political obstacles cripple implementation of this key provision and even deter open acknowledgment of the problem by countries (Bjørnstad, Tekle, and Göransson 2013). This lack of access to genetic resources can be an impediment to development and deployment of traits needed for crop adaptation to climate change.

In recent years there has, however, been progress in securing the conservation of plant genetic resources. The Global Crop Diversity Trust established an endowment to provide ongoing funding to important collections. Norway constructed and—together with the Nordic Genetic Resource Centre and the Global Crop Diversity Trust—oversees the Svalbard Global Seed Vault, which functions as a safety net for the emerging international *ex situ* conservation system for seed crops (Westengen, Jeppson, and Guarino 2013; Fowler 2008). By the end of 2017, nearly 1,000,000 safety duplicates of accessions (varieties or populations) held in more than 60 genebanks were conserved at Svalbard.

Successful adaptation of crops to climate change will be required for the world to avoid significant increases in hunger, malnutrition, political instability, and environmental destruction. Additional investments will need to be made in crop diversity collection and conservation, in the screening of collections for useful traits, and particularly in plant-breeding programs, including for those crops for which there is little or no effort under way presently. Such efforts are a basic prerequisite for crop adaptation. If crops do not successfully adapt to climate change, neither will agriculture and neither will we.

REFERENCES

Battisti, David S., and Rosamond L. Naylor. 2009. "Historical warnings of future food insecurity with unprecedented seasonal heat." *Science* 323 (5911): 240–244.

Bellon, M. R., D. Hodson, and J. Hellin. 2011. "Assessing the vulnerability of traditional maize seed systems in Mexico to climate change." *Proceedings of the National Academy of Sciences* 108 (33): 13432–13437.

Bjørnstad, Åsmund, Selamawit Tekle, and Magnus Göransson. 2013. "'Facilitated access' to plant genetic resources: Does it work?" *Genetic Resources and Crop Evolution* 60 (7): 1959–1965.

Burke, M. B., D. B. Lobell, and L. Guarino. 2009. "Shifts in African crop climates by 2050, and the implications for crop improvement and genetic resources conservation." *Global Environmental Change: Human and Policy Dimensions* 19 (3): 317–325. https://doi.org/10.1016/j.gloenvcha.2009.04.003.

Büntgen, Ulf, Willy Tegel, Kurt Nicolussi, Michael McCormick, David Frank, Valerie Trouet, Jed O. Kaplan, Franz Herzig, Karl-Uwe Heussner, and Heinz Wanner. 2011. "2500 years of European climate variability and human susceptibility." *Science* 331 (6017): 578–582.

Cairns, Jill E., Jose Crossa, P. H. Zaidi, Pichet Grudloyma, Ciro Sanchez, Jose Luis Araus, Suriphat Thaitad, Dan Makumbi, Cosmos Magorokosho, and Marianne Bänziger. 2013. "Identification of drought, heat, and combined drought and heat tolerant donors in maize." *Crop Science* 53 (4): 1335–1346.

Carroll, Scott P., Peter Sogaard Jorgensen, Michael T. Kinnison, Carl T. Bergstrom, R. Ford Denison, Peter Gluckman, Thomas B. Smith, Sharon Y. Strauss, and Bruce E. Tabashnik. 2014. "Applying evolutionary biology to address global challenges." *Science* 346 (6207): art. 1245993.

Challinor, A. J., J. Watson, D. B. Lobell, S. M. Howden, D. R. Smith, and N. Chhetri. 2014. "A meta-analysis of crop yield under climate change and adaptation." *Nature Climate Change* 4 (4): 287–291.

Challinor, Andrew J., A.-K. Koehler, Julian Ramirez-Villegas, S. Whitfield, and B. Das. 2016. "Current warming will reduce yields unless maize breeding and seed systems adapt immediately." *Nature Climate Change* 6 (10): 954–958.

Cossani, C. Mariano, and Matthew P. Reynolds. 2012. "Physiological traits for improving heat tolerance in wheat." *Plant Physiology* 160 (4): 1710–1718.

Davis, Aaron P., Tadesse Woldemariam Gole, Susana Baena, and Justin Moat. 2012. "The impact of climate change on indigenous arabica coffee (*Coffea arabica*): Predicting future trends and identifying priorities." *PLOS One* 7 (11): e47981.

FAO. 2010. *The Second Report on the State of the World's Plant Genetic Resources*. FAO.

FAO. 2014. "FAOSTAT." http://faostat3.fao.org/home/index.html.

FAO, IFAD, and WFP. 2016. *The State of Food Insecurity in the World: Meeting the 2015 International Hunger Targets: Taking Stock of Uneven Progress*. Food and Agriculture Organization, International Fund for Agricultural Development, World Food Program.

Fowler, C., and T. Hodgkin. 2004. "Plant genetic resources for food and agriculture: Assessing global availability." *Annual Review of Environment and Resources* 29: 143–179. https://doi.org/10.1146/annurev.energy.29.062403.102203.

Fowler, Cary. 1994. *Unnatural Selection: Technology, Politics, and Plant Evolution*. Vol. 6. Gordon and Breach Yverdon.

Fowler, Cary. 2008. "The Svalbard seed vault and crop security." *BioScience* 58 (3): 190–191.

High Level Panel of Experts. 2012. *Food Security and Climate Change: A Report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security*. FAO.

Hsiang, Solomon M., Marshall Burke, and Edward Miguel. 2013. "Quantifying the influence of climate on human conflict." *Science* 341 (6151): 1235367.

Jarvis, Andy, Annie Lane, and Robert J. Hijmans. 2008. "The effect of climate change on crop wild relatives." *Agriculture Ecosystems and Environment* 126 (1–2): 13–23. https://doi.org/10.1016/j.agee,2008.01.013.

Khoury, Colin K., Harold A. Achicanoy, Anne D. Bjorkman, Carlos Navarro-Racines, Luigi Guarino, Ximena Flores-Palacios, Johannes M. M. Engels, John H. Wiersema, Hannes Dempewolf, and Steven Sotelo. 2016. "Origins of food crops connect countries worldwide." *Proceedings of the Royal Society B* 283: art. 20160792.

Larson, Greger, Dolores R. Piperno, Robin G. Allaby, Michael D. Purugganan, Leif Andersson, Manuel Arroyo-Kalin, Loukas Barton, Cynthia Climer Vigueira, Tim Denham, and Keith Dobney. 2014. "Current perspectives and the future of domestication studies." *Proceedings of the National Academy of Sciences* 111 (17): 6139–6146.

Lesk, Corey, Pedram Rowhani, and Navin Ramankutty. 2016. "Influence of extreme weather disasters on global crop production." *Nature* 529 (7584): 84–87.

Lira, Rafael, Oswaldo Téllez, and Patricia Dávila. 2009. "The effects of climate change on the geographic distribution of Mexican wild relatives of domesticated Cucurbitaceae." *Genetic Resources and Crop Evolution* 56 (5): 691–703.

Lobell, D. B., and M. B. Burke. 2010. "On the use of statistical models to predict crop yield responses to climate change." *Agricultural and Forest Meteorology* 150 (11): 1443–1452.

Lobell, D. B., M. Bänziger, C. Magorokosho, and B. Vivek. 2011. "Nonlinear heat effects on African maize as evidenced by historical yield trials." *Nature Climate Change* 1 (1): 42–45.

Lobell, David B., and Sharon M. Gourdji. 2012. "The influence of climate change on global crop productivity." *Plant Physiology* 160 (4): 1686–1697.

Lobell, David B., Wolfram Schlenker, and Justin Costa-Roberts. 2011. "Climate trends and global crop production since 1980." *Science* 333 (6042): 616–620.

McCouch, Susan, Gregory J. Baute, James Bradeen, Paula Bramel, Peter K. Bretting, Edward Buckler, John M. Burke, David Charest, Sylvie Cloutier, and Glenn Cole. 2013. "Agriculture: Feeding the future." *Nature* 499 (7456): 23–24.

McGuire, Shawn, and Louise Sperling. 2013. "Making seed systems more resilient to stress." *Global Environmental Change: Human and Policy Dimensions* 23 (3): 644–653.

Myers, Samuel S., Antonella Zanobetti, Itai Kloog, Peter Huybers, Andrew D. B. Leakey, Arnold J. Bloom, Eli Carlisle, Lee H. Dietterich, Glenn Fitzgerald, and Toshihiro Hasegawa. 2014. "Increasing CO_2 threatens human nutrition." *Nature* 510 (7503): 139–142.

Peng, Shaobing, Jianliang Huang, John E. Sheehy, Rebecca C. Laza, Romeo M. Visperas, Xuhua Zhong, Grace S. Centeno, Gurdev S. Khush, and Kenneth G. Cassman. 2004. "Rice yields decline with higher night temperature from global warming." *Proceedings of the National Academy of Sciences* 101 (27): 9971–9975.

Plucknett, Donald, Nigel J. H. Smith, J. T. Williams, and N. Murthi Anishetty. 1987. *Gene Banks and the World's Food*. Los Baños, Philippines: International Rice Resource Institute.

Porter, J. R., L. Xie, A. J. Challinor, K. Cochrane, S. M. Howden, M. M. Iqbal, D. B. Lobell, and M. I. Travasso. 2014. "Food security and food production systems." In *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea, and L. L. White, 485–533. Cambridge University Press.

Rippke, U., J. Ramirez-Villegas, A. Jarvis, S. J. Vermeulen, L. Parker, F. Mer, B. Diekkrüger, A. J. Challinor, and M. Howden. 2016. "Timescales of transformational climate change adaptation in sub-Saharan African agriculture." *Nature Climate Change* 6: 605–609.

Schlenker, W., and D. B. Lobell. 2010. "Robust negative impacts of climate change on African agriculture." *Environmental Research Letters* 5 (1): 014010. https://doi.org/10.1088/1748–9326/5/1/014010.

Theisen, Ole Magnus, Nils Petter Gleditsch, and Halvard Buhaug. 2013. "Is climate change a driver of armed conflict?" *Climatic Change* 117 (3): 613–625.

Thomas, Chris D., Alison Cameron, Rhys E. Green, Michel Bakkenes, Linda J. Beaumont, Yvonne C. Collingham, Barend F. N. Erasmus, Marinez Ferreira De Siqueira, Alan Grainger, and Lee Hannah. 2004. "Extinction risk from climate change." *Nature* 427 (6970): 145–148.

Thornton, P. K., P. G. Jones, G. Alagarswamy, and J. Andresen. 2009. "Spatial variation of crop yield response to climate change in East Africa." *Global Environmental Change: Human and Policy Dimensions* 19 (1): 54–65. https://doi.org/10.1016/j.gloenvcha.2008.08.005.

Ureta, Carolina, Enrique Martínez-Meyer, Hugo R. Perales, and Elena R. Álvarez-Buylla. 2012. "Projecting the effects of climate change on the distribution of maize races and their wild relatives in Mexico." *Global Change Biology* 18 (3): 1073–1082.

Vermeulen, Sonja J., Andrew J. Challinor, Philip K. Thornton, Bruce M. Campbell, Nishadi Eriyagama, Joost M. Vervoort, James Kinyangi, Andy Jarvis, Peter Läderach, and Julian Ramirez-Villegas. 2013. "Addressing uncertainty in adaptation planning for agriculture." *Proceedings of the National Academy of Sciences* 110 (21): 8357–8362.

Von Uexkull, N., M. Croicu, H. Fjelde, and H. Buhaug. 2016. "Civil conflict sensitivity to growing-season drought." *Proceedings of the National Academy of Sciences* 113: 12391–12396.

Westengen, Ola T., and Anne K. Brysting. 2014. "Crop adaptation to climate change in the semi-arid zone in Tanzania: The role of genetic resources and seed systems." *Agriculture and Food Security* 3 (1): 3.

Westengen, Ola T., Simon Jeppson, and Luigi Guarino. 2013. "Global ex-situ crop diversity conservation and the Svalbard Global Seed Vault: Assessing the current status." *PLOS One* 8 (5): e64146.

Ziska, Lewis H., Dana M. Blumenthal, G. Brett Runion, E. Raymond Hunt Jr., and Hilda Diaz-Soltero. 2011. "Invasive species and climate change: an agronomic perspective." *Climatic Change* 105 (1–2): 13–42.